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E 0336–248 : A NEW BL LAC OBJECT FOUND BY AN OLD *EINSTEIN*

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ABSTRACT

We obtained new *ROSAT* HRI and optical observations in the field of the *Einstein* X-ray source E 0336–248, which we use to identify it as a 19th magnitude BL Lacertae object at $z = 0.251$ with $L_X = 1 \times 10^{45}$ erg s^{−1}. It is also a 14 mJy radio source at 20 cm. An emission-line galaxy at $z = 0.043$ that was previously considered a Seyfert identification for E 0336–248 is shown instead to be an unrelated, non-active H II region galaxy that lies 78'' from the X-ray source. The resolution of this historical case of mistaken identity illustrates that discoveries of non-AGN emission-line galaxies with high X-ray luminosity should be tested carefully. The properties of E 0336–248 are similar to those of other X-ray selected BL Lacs, including its location in an apparent group or cluster of galaxies. Somewhat unusual is the weak contribution of nonstellar optical light relative to the starlight in the spectrum of its host galaxy, which raises once again the possibility that even high-luminosity BL Lac objects may be difficult to identify in X-ray selected samples. We discuss a possible manifestation of this problem that appeared in the recent literature.

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1. INTRODUCTION

Pravdo & Marshall (1984) classified the serendipitous *Einstein* IPC X-ray source E 0336–248 as a narrow-line AGN at $z = 0.043$ on the basis of a low-resolution optical spectrum that they obtained of an anonymous galaxy near the X-ray position. Consequently, this object appears in standard AGN catalogs (Veron-Cetty & Veron 1996, Hewitt & Burbidge 1983), as well as in a list of bright quasars to be used in absorption-line studies with the *HST* (Bowen et al. 1994). Although bright enough, E 0336–248 was not included in the *Einstein* Medium Sensitivity Survey (Stocke et al. 1991) because it fell close to a window support rib of the IPC detector. We became suspicious of the optical identification of E 0336–248 when our own higher resolution optical spectra, taken for the purpose of studying the nature of narrow-line X-ray galaxies, revealed only H II region emission lines, and no AGN features. The implied X-ray luminosity of $\approx 3 \times 10^{43}$ erg s $^{-1}$ would be far in excess of that observed from any non-AGN starforming galaxy. We concluded that either E 0336–248 is a highly unusual galaxy, or more likely, the identification of it with the X-ray source is incorrect. Meanwhile, another serendipitous observation of E 0336–248 had been made, this time with the *ROSAT* PSPC, but since both the IPC and the PSPC X-ray positions were obtained far off-axis in their respective detectors, neither was reliable enough to establish the identification unambiguously. Therefore, we obtained an additional X-ray observation with the *ROSAT* HRI, enabling us to make a firm identification with a much fainter optical object that turned out to be a BL Lac object at $z = 0.251$ as measured from stellar absorption features in its optical spectrum. In the remainder of this paper, we describe the optical and X-ray data collected in the course of this investigation, and discuss some of the implications of the outcome.

2. THE WRONG GALAXY

We obtained our first optical spectrum of the galaxy near E 0336–248 from Bob Becker, who kindly observed it for us with the lens-grism spectrograph at Lick Observatory on 1988 September 13. As shown in Figure 1a, this spectrum reveals no AGN features. The absence of any [O III] $\lambda 5007$ emission, despite the presence of weak H β , raised serious doubts about its classification as an AGN. (The slight broadening of H β is due to poor focus in the spectrograph, and is therefore not indicative of AGN activity.) Since the spectrum obtained by Pravdo & Marshall (1984) was of even lower resolution than this one, we considered it likely that their Seyfert classification was mistaken. Nevertheless, we decided to obtain a higher resolution spectrum to look for weak, broad H α emission that is sometimes the only evidence of an active nucleus in X-ray selected AGNs, before declaring there to be a problem with the identification.

Accordingly, we observed the galaxy with the Goldcam CCD spectrometer on the KPNO 2.1m telescope on 1995 January 23. A resolution of 4.2 Å was achieved using a 600 lines mm $^{-1}$ grating blazed at 6750 Å and a slit width of 1."8. The wavelength range covered was 5500–8500 Å. The heliocentric redshift that we measure from this spectrum is 0.04255 ± 0.00005 . The portion of the spectrum containing the H α line is shown in Figure 1b. There are decidedly no AGN features in this spectrum. The velocity widths of H α and [N II] are consistent with the instrumental resolution, yielding a conservative upper limit on their FWHM of 80 km s $^{-1}$. The [N II] $\lambda 6583$ /H α ratio is 0.37, typical of H II region galaxies. There is no additional broad component of H α present. Despite the glaring absence of AGN features in this particular spectrum, the possibility that it might contain a highly variable AGN in a quiescent phase could not be rejected out of hand. Nor could we evaluate the possibility that the galaxy makes a partial contribution to a confused or extended X-ray source. Therefore, the definitive test would have to come from a high resolution X-ray observation with the *ROSAT* HRI.

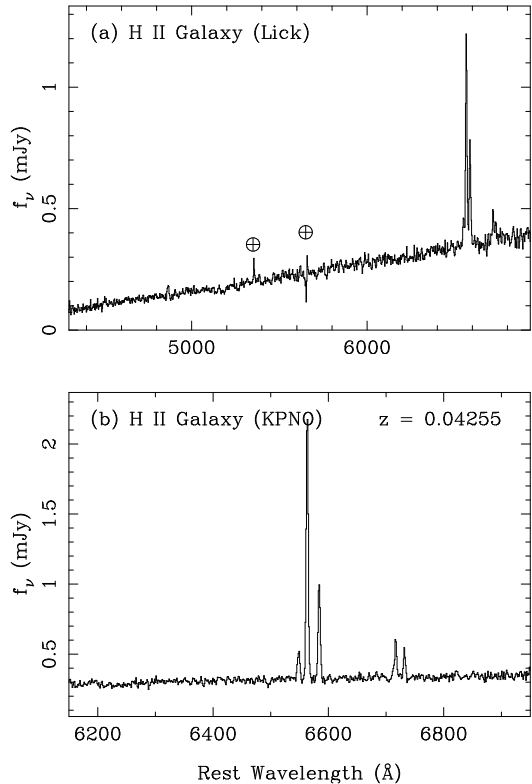


FIGURE 1. – Two spectra of the previously believed counterpart of E 0336–248, shifted to its rest frame. Neither show any AGN features. (a) Spectrum obtained at Lick Observatory. Note the absence of [O III] $\lambda 5007$ or other Seyfert-like features. (b) Higher resolution spectrum obtained on the KPNO 2.1m telescope. The width of the emission lines is consistent with the instrumental resolution of 4.2 \AA .

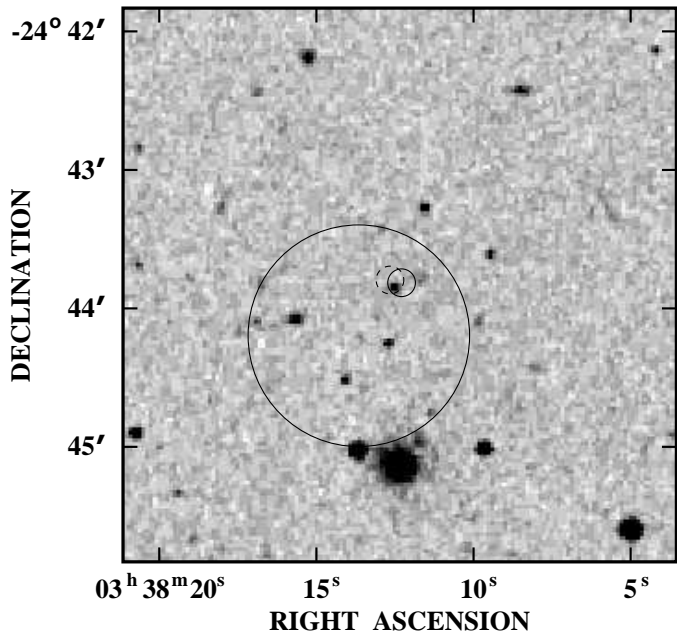


FIGURE 2. – Finding chart for E 0336–248 from the digitized SERC Sky Survey IIIa-J plate. X-ray error circles from the *Einstein* IPC and *ROSAT* HRI are shown; the dashed circle is from the second HRI observation. The optical position of the BL Lac object within the HRI error circles is (J2000) $3^{\text{h}}38^{\text{m}}12^{\text{s}}50$, $-24^{\circ}43'50''.3$. The unrelated H II galaxy is the brightest object just south of the IPC error circle, at (J2000) $3^{\text{h}}38^{\text{m}}12^{\text{s}}39$, $-24^{\circ}45'07''.8$.

3. X-RAY OBSERVATIONS

3.1 X-ray Position

We conducted a *ROSAT* HRI observation of E 0336–248 on 1996 Jan. 17 for 3616 s. A single, pointlike X-ray source was detected at (J2000) $3^{\text{h}}38^{\text{m}}12^{\text{s}}29$, $-24^{\circ}43'48''.9$ with a count rate of $0.0497 \pm 0.0038 \text{ s}^{-1}$. Figure 2 is a finding chart made from the digitized SERC Southern Sky Survey IIIa-J plate, showing the *ROSAT* HRI error circle of radius $6''$, as well as the larger *Einstein* IPC error circle of radius $48''$. The *ROSAT* position unambiguously determines the correct identification with a ≈ 19 mag object at (J2000) $3^{\text{h}}38^{\text{m}}12^{\text{s}}50$, $-24^{\circ}43'50''.3$. In addition there is a 20 cm radio source of flux density $14.0 \pm 1.1 \text{ mJy}$ at (J2000) $3^{\text{h}}38^{\text{m}}12^{\text{s}}93$, $-24^{\circ}43'51''.9$, within $6''$ of the optical object, in the NRAO VLA Sky Survey (NVSS, Condon et al. 1997). The positional difference is within the expected error of that survey.

The bright galaxy previously thought to be the identification of the X-ray source lies at (J2000) $3^{\text{h}}38^{\text{m}}12^{\text{s}}39, -24^{\circ}45'07''.8$, just south of the *Einstein* IPC error circle. It is $78''$ from the actual X-ray source. Since this galaxy is not detected in X-rays, we can place an upper limit on its X-ray luminosity that is about a factor of 30 smaller than previously thought, or less than 10^{42} erg s $^{-1}$. Virtually all H II region galaxies fall below this limit (Moran, Halpern, & Helfand 1994, 1996; Halpern, Helfand, & Moran 1995). It is also not detected in the NVSS.

Although the *ROSAT* HRI observation of E 0336–248 was entirely successful, an error in the processing software mistakenly concluded otherwise, which led to the automatic scheduling of an additional observation 7 months later. Despite our protestations that no more data were needed, a second observation of 3262 s duration was carried out on 1996 Aug. 8–9. The same source was detected at the overlapping position (J2000) $3^{\text{h}}38^{\text{m}}12^{\text{s}}66, -24^{\circ}43'47''.7$, as shown by the dashed circle in Figure 2. Thus, the optical identification was confirmed, albeit with a reduced count rate of 0.0275 ± 0.0030 s $^{-1}$. While it is comforting to know that the X-ray source is variable in flux but not in position, it is disconcerting that human intervention was not possible to prevent an unintended *ROSAT* pointing from being made.

3.2 X-ray Spectral Fitting

As mentioned above, E 0336–248 was also observed serendipitously $36'$ off-axis in a *ROSAT* PSPC observation of 49,500 s duration on 1991 August 14–15. In order to extract a reasonably reliable spectrum, we used a circular extraction aperture of diameter $12'$, which is large enough to contain $\geq 95\%$ of the photons with energies below 2 keV for a point source at the given off-axis distance (Hasinger et al. 1994). Background events were taken from an aperture at the same off-axis distance and adjacent to the target extraction aperture. This was done to avoid regions on the detector that are shadowed by the PSPC window support structure. The light curve of the target and background were examined to exclude periods of high background level, resulting in an accepted exposure time of 39,048 s.

The PSPC response matrix is not reliable at energies above ~ 2 keV (Turner, Urry, & Mushotzky 1993). The following spectral analysis is therefore limited to the range $0.1 < E < 2.0$ keV. The results of a simple power-law model fit to the observed spectrum are given in Table 1 and shown in Figure 3 along with the χ^2 confidence contours of the fit. The power-law model with energy index $\alpha = 1.14 \pm 0.25$ is an adequate representation of the observed spectrum, with $\chi^2_{\nu} = 1.111$ for 26 degrees of freedom, and no significant improvement was achieved with other models. The fitted column density, $N_{\text{H}} = 1.85 \times 10^{20}$ cm $^{-2}$, is consistent with the Galactic value of 1.36×10^{20} cm $^{-2}$ (Stark et al. 1992), considering that the uncertainty on the latter is $\sim 1 \times 10^{20}$ cm $^{-2}$ (Elvis, Lockman, & Fassnacht 1994). Knowing that the correct redshift is 0.251 (see §4), the rest-frame 0.1–2.0 keV luminosity of E 0336–248 is 1.14×10^{45} erg s $^{-1}$ ($H_0 = 50$ km s $^{-1}$ Mpc $^{-1}$, $q_0 = \frac{1}{2}$) after correcting for absorption. Among all four X-ray observations of E 0336–248, one by *Einstein* and three by *ROSAT*, the observed 0.1–2.0 keV flux ranges from 1.5×10^{-12} erg cm $^{-2}$ s $^{-1}$ to 3.3×10^{-12} erg cm $^{-2}$ s $^{-1}$.

4. THE CORRECT OPTICAL IDENTIFICATION

Armed with the precise HRI position and the single coincident optical object seen in Figure 3, we returned to Lick Observatory for spectroscopic identification. The object was observed with the 3m Shane reflector and Kast spectrograph (Miller & Stone 1987) for 2400 s on 1996 October 11. The spectrum, which covers the range 4700–7470 Å, was obtained through a $2''$ slit and was reduced in a standard manner. The flux calibrated spectrum is shown in Figure 4, after dereddening assuming a Seaton (1979) law and color excess $E(B - V) = 0.026$, and shifting to the rest frame of what is obviously an old stellar population at $z = 0.2509 \pm 0.0005$. The resemblance of its spectrum

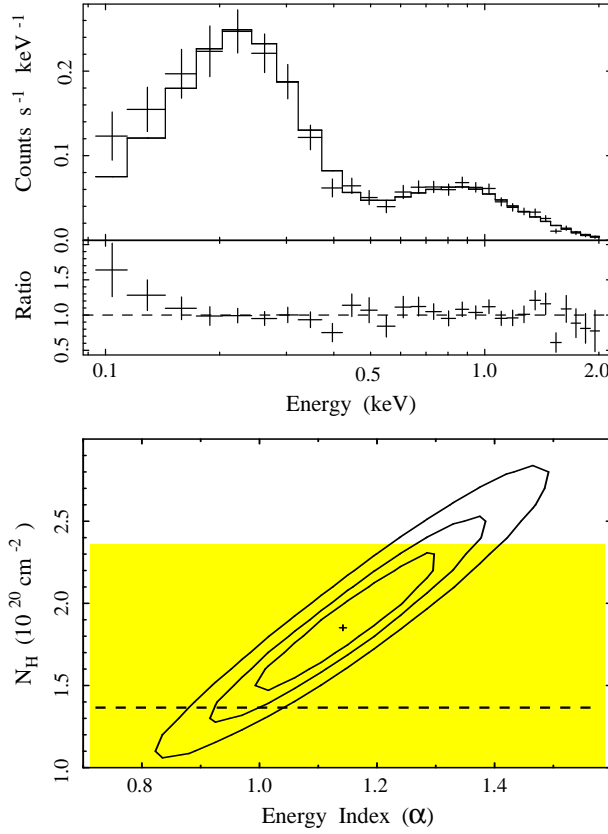


FIGURE 3. – The *ROSAT* PSPC spectrum of E 0336–248 showing the best fitting power-law model and the data divided by the folded model. Also shown are the confidence contours of the power-law model fit. These contours represent the 68%, 90%, and 99% confidence limits for two interesting parameters. The dashed line represents the Galactic N_{H} .

to an elliptical galaxy, the absence of any obvious emission lines, and the association with an x-ray source of $L_{\text{X}} \approx 1 \times 10^{45} \text{ erg s}^{-1}$, all suggest that E 0336–248 is a BL Lac object. The evidence for a nonstellar contribution to the optical light (a hallmark of BL Lac objects) is definite but subtle. In comparison with normal elliptical galaxies such as NGC 4339, the spectrum of E 0336–248 is bluer. When the two spectra are normalized at 6000 Å as in Figure 4, the BL Lac spectrum is higher by 40% at 4000 Å. The Ca II H&K line have larger equivalent widths in the template galaxy, 23.5 Å in NGC 4339 vs. 13.5 Å in E 0336–248.

In order to quantify the contribution of a featureless power law to the optical spectrum, we fitted it with a model consisting of a linear combination of starlight and a power law of the form $f_{\nu} \propto \nu^{-\alpha}$. The fit was carried out by exploring a range of values of the power-law index in discrete

Table 1: The *ROSAT* PSPC
Observation of E 0336–248

Observational details	
$\alpha_{(2000)}$	03 ^h 38 ^m 12 ^s .29
$\delta_{(2000)}$	−24° 43′ 48″.9
z	0.2509
$N_{\text{H}}^{\text{Gal}} (\text{cm}^{-2})$ ^a	$(1.36 \pm 1.0) \times 10^{20}$
Date (UT)	1991 Aug 14–15
$T_{\text{obs}} (\text{s})$	39,048
Off-axis distance ...	36′
Count rate (s^{-1}) ^b .	0.112 ± 0.003
Power-law model ^c	
α	$1.14^{+0.26}_{-0.23}$
$A (\mu\text{Jy})$ ^d	$(0.449^{+0.045}_{-0.041})$
$N_{\text{H}} (\text{cm}^{-2})$	$(1.85^{+0.69}_{-0.60}) \times 10^{20}$
$\chi^2_{\nu} (\nu)$	1.111 (26)
$F_{\text{X}} (\text{erg cm}^{-2} \text{ s}^{-1})$ ^b	$(2.14^{+0.13}_{-0.11}) \times 10^{-12}$
$L_{\text{X}} (\text{erg s}^{-1})$ ^e	$(1.14^{+0.44}_{-0.27}) \times 10^{45}$

^a Galactic neutral hydrogen column density from Stark et al. (1992).

^b 0.1–2.0 keV observed frame, corrected for background and vignetting.

^c Errors are 90% confidence for 2 interesting parameters.

^d Normalization at 1 keV observed frame.

^e 0.1–2.0 keV rest frame ($H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $q_0 = \frac{1}{2}$), corrected for absorption.

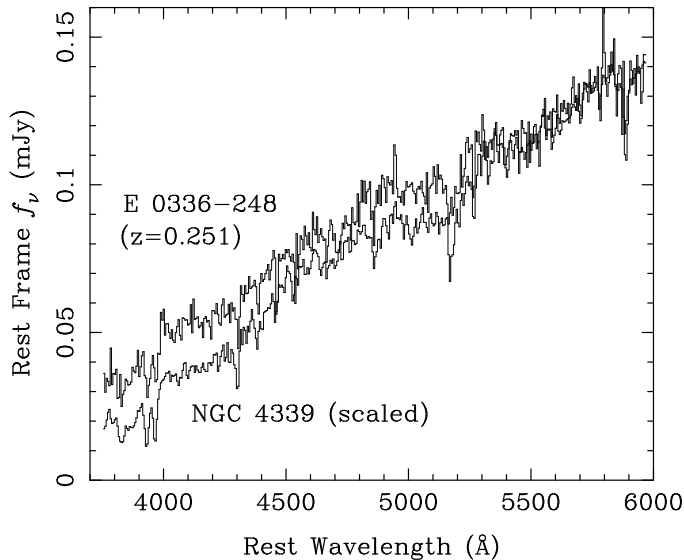


FIGURE 4. – Optical spectrum of the BL Lac object identified with E 0336–248, compared with a spectrum of the elliptical galaxy NGC 4339. The latter has been normalized to E 0336–248 at 6000 Å.

steps, and determining the linear combination coefficients at each step by minimizing the r.m.s. deviation of the model from the data. To represent the starlight we used the spectra of a number of elliptical galaxies as templates. The galaxies used span a range of morphological types (E0–E6) and include NGC 3379, NGC 4339, NGC 4365, NGC 5322, IC 4889, and the composite giant elliptical galaxy of Yee & Oke (1978). We find that a reasonable fit can be achieved for all template galaxy spectra and that a featureless continuum must be present because the spectrum of E 0336–248 is flatter (bluer) than any of the template galaxy spectra. The decomposition into starlight and a featureless power-law continuum yields a power-law index $\alpha = 1.3 \pm 0.2$. The uncertainty is systematic and is dominated by our lack of knowledge of the exact stellar population of the host galaxy. The error bar quoted above represents the dispersion in the power-law indices obtained using different galaxy spectra as templates. In the best-fitted decomposition, the underlying galaxy contributes $(27 \pm 4)\%$ of the light just blueward of the Ca II H&K break and $(45 \pm 4)\%$ just redward of it. In the *B* and *V* bands the galaxy contributes $(55 \pm 3)\%$ and $(63 \pm 3)\%$ of the light, respectively. Since the galaxy contribution in the rest-frame *V* band is ≈ 19.2 mag, its absolute *V* magnitude is -21.8 at the luminosity distance of 1590 Mpc. The galaxy is probably ~ 0.3 mag brighter than this, or ≈ -22.1 , when account is taken of its light falling outside the spectrograph slit.

5. DISCUSSION AND CONCLUSIONS

The observed properties of E 0336–248 are typical of those of other BL Lac objects discovered by *Einstein*. In particular, its X-ray spectral index α is 1.1, and all but 1 of the 22 BL Lacs in the *Einstein* Medium Sensitivity Survey (EMSS) that were observed by *ROSAT* (Perlman et al. 1996a) have $0.6 < \alpha < 1.9$. Similarly, the broad-band properties of E 0336–248 in radio, optical, and X-ray, place it in the distinctive location populated by X-ray selected BL Lacs in the $(\alpha_{\text{ro}}, \alpha_{\text{ox}})$ diagram (Stocke et al. 1990; Lamer et al. 1996; Perlman et al. 1996b). We estimate $\alpha_{\text{ro}} = 0.45$

and $\alpha_{\text{ox}} = 0.87$ using the total optical flux at 5500 Å observed wavelength, the 6 cm radio flux extrapolated with a flat spectrum to 20 cm, and the X-ray flux at 2 keV.

It is common for BL Lac objects to be found in groups or clusters of galaxies (Falomo 1996; Pesce, Falomo, & Treves 1995). Around E 0336–248, we can see faint images on the SERC and ESO Sky Survey plates which may be an association of galaxies in which it resides. One of these objects, 25'' south of the BL Lac object in Figure 2, is especially blue. We obtained a spectrum of it which is of insufficient quality to make a firm classification. It has no strong emission or absorption features. In fact, we originally suspected it as the X-ray source, but the HRI observations clearly show that this is not the case. Nevertheless, it would be interesting to find out the nature of this neighboring object.

It is interesting to consider how the optical properties of the host galaxy of E 0336–248 relate to the completeness of samples of X-ray selected BL Lac objects. Because the fractional contribution of nonstellar optical emission is relatively small in this object, its spectrum differs from that of an ordinary elliptical galaxy only in subtle ways. In particular, the depth of the Ca II H&K break, where the flux drops by about 50% in normal elliptical galaxies, is the strongest indicator of dilution by nonstellar optical light. In E 0336–248, the flux drops by 33% at the break, which doesn’t even meet Stocke’s nominal criterion of < 25% for classification as a BL Lac (Stocke et al. 1991; Morris et al. 1991). This raises a concern about the prospects of spectroscopic identification of BL Lacs in more luminous galaxies, because the absolute magnitude of the host galaxy of E 0336–248 is only $M_V \approx -22.1$. Host galaxies of BL Lacs are typically more luminous, having $\langle M_R \rangle$ in the range -23.1 to -23.5 (Falomo 1996; Wurtz, Stocke, & Yee 1996), and total range $-21.7 < M_R < -24.4$. Assuming $V - R = 0.9$, this makes E 0336–248 at $M_R \approx -23.0$ slightly less luminous than average. If its host galaxy were as little as 1 mag brighter, all other things being equal, it would be virtually impossible to detect the dilution by nonstellar light in ground-based spectroscopy.

Fortunately, radio emission supports the identification; there is still no good evidence of the long-sought radio-quiet BL Lacs. However, there is seemingly justified recurrent speculation (e.g., Browne & Marchã 1993) that a population of low-luminosity BL Lacs remains undiscovered in X-ray selected samples because of the spectroscopic contrast problem described above. Long ago, we speculated that even highly luminous BL Lacs might be misclassified as either “normal” galaxies or cluster X-ray sources because their optical nucleus can be camouflaged by a luminous host galaxy (Halpern et al. 1986). We revive that worry here, imagining E 0336–248 in a bigger galaxy as a possible model. In fact, the unusual galaxy J2310–43 recently described by Tananbaum et al. (1997) might be just such an object. It is less luminous than E 0336–248 by a factor $\approx 6 - 7$ in X-rays and ≈ 2 in radio, yet it is in a more luminous galaxy of $M_R = -23.5$. The principal obstacle to interpreting the origin of its $> 10^{44}$ erg s $^{-1}$ X-ray emission is the absence of evidence of nuclear activity in the optical spectrum. But if J2310–43 hosts a BL Lac with the same nuclear spectral energy distribution as E 0336–248, then the dilution of its starlight spectrum by its optical nonstellar continuum would be negligible, which seems to be consistent with observations. For this reason we regard the BL Lac hypothesis for J2310–43, considered by Tananbaum et al. (1997), as quite plausible.

Finally, we repeat our plea for high-quality optical spectroscopy when classifying narrow emission-line galaxies. Unlike the H II galaxy misidentification reported here, two other ambiguous narrow-line spectra from Pravdo & Marshall (1984), E 0116+317 and E 1242+165, were subsequently classified as bona-fide Seyfert galaxy X-ray sources in the EMSS (Stocke et al. 1991). The latter is by far the more common outcome. To paraphrase Halpern et al. (1995), there are still no X-ray luminous starburst galaxies.

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